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Michael E. Tauber

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Michael E. Tauber, Ames Research Center, Moffett Field, California

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Ames Research Center
Moffett Field, California 94035

SUMMARY

Newtonian theory is used to derive a simple expression for the maximum lift/drag ratio of flat plates with bluntness and skin friction at hypersonic speeds. The bluntness drag is assumed to be independent of angle of attack. Because the effect of skin friction is of second order over the angle of attack range for maximum lift/drag ratio, it has been assumed constant. As an example, the expression is applied to the Space Shuttle.

The concept of Newtonian aerodynamic theory has been extensively applied to hypersonic flows (ref. 1). The theory is widely used to estimate the aerodynamics of vehicles at hypersonic speeds in continuum flow. Because the lifting surfaces of hypersonic vehicles frequently approximate flat plates, simple relations can be used for estimating the aerodynamic properties of such shapes. Here, a simple expression is derived for the maximum lift/drag ratio of a flat plate with skin friction and bluntness. The resulting expression will be applied to the Space Shuttle.

The pressure coefficient for Newtonian flow on a flat plate at an angle of attack, α, is

$$C_p = 2 \sin^2 \alpha \tag{1}$$

The pressure is resolved into components which are normal to the free stream velocity for determining lift and which are parallel to the free stream for determining the drag component. The skin friction coefficient of the plate is C_{F_o}, while the drag coefficient due to bluntness, C_{D_o}, is assumed to be independent of angle of attack. The expressions for the lift and drag coefficients are

$$C_L = C_p \cos \alpha - C_{F_o} \sin \alpha = 2 \sin^2 \alpha \cos \alpha - C_{F_o} \sin \alpha \tag{2a}$$

$$C_D = C_p \sin \alpha + C_{F_o} \cos \alpha + C_{D_o} = 2 \sin^3 \alpha + C_{F_o} \cos \alpha + C_{D_o} \tag{2b}$$

The lift/drag ratio is

$$\frac{L}{D} = \frac{2 \sin^2 \alpha \cos \alpha - C_{F_o} \sin \alpha}{2 \sin^3 \alpha + C_{F_o} \cos \alpha + C_{D_o}} \tag{3}$$

To find the maximum lift/drag ratio, equation (3) is differentiated with respect to α and set equal to zero

$$\frac{d(L/D)}{d\alpha} = 0 \tag{4}$$

The resulting transcendental equation gives the angle of attack, α_*, for the maximum lift/drag ratio

$$\sin^4 \alpha_* - C_{F_o} \sin \alpha_* \cos \alpha_* + \frac{C_{F_o}^2}{4} - \frac{C_{D_o}}{4} (4 \sin \alpha_* - 6 \sin^3 \alpha_* - C_{F_o} \cos \alpha_*) = 0 \tag{5}$$

Although equation (5) can be readily solved numerically, it can also be reduced to a simple expression by eliminating high-order terms. Because the skin friction coefficient is $O(10^{-3})$ and the bluntness drag coefficient is $O(10^{-2})$,

$$C_{F_o}^2 \approx O(10^{-6})$$

$$C_{F_o} C_{D_o} \approx O(10^{-5})$$

In general, $\alpha_* < 20°$ and therefore

$$\sin^2 \alpha_* \ll 1$$

$$\cos \alpha_* \doteq 1$$

Using these approximations, equation (5) reduces to

$$\sin \alpha_* \doteq (C_{D_o} + C_{F_o})^{1/3} \tag{6}$$

By substituting equation (6) into equation (3) and again invoking the above approximations

$$\left(\frac{L}{D}\right)_{max} \doteq \frac{2}{3(C_{D_o} + C_{F_o})^{1/3}} \tag{7a}$$

or alternatively

$$\left(\frac{L}{D}\right)_{max} \doteq \frac{2}{3 \sin \alpha_*} \tag{7b}$$

Results from the approximate relations of equations (6) and (7) are compared, in figure 1, with those from the exact expressions given by equations (3) and (5). A skin friction coefficient of 0.002 has been assumed. The maximum error in the

approximation for α_* is about 1°, or 5% for values of $C_{D_o} \leq 0.04$. The error in equation (7) for the maximum lift/drag ratio varies from 1.8% to 6.6%.

In reference 2, the maximum hypersonic lift/drag ratio of the Space Shuttle is given as 1.9 at about $\alpha_* = 17.5°$. Using $\alpha_* = 17.5°$, the lift/drag ratio value derived from equation (7b) is 2.2, a difference of 15%. The exact expression, equation (3), yields a value of 2.0, or a 5% difference using $C_{F_o} = 0.002$. Because the lifting surface of the Shuttle is not precisely a flat plate,[1] the agreement is considered reasonable.

Care should be taken that the approximate equations (eqs. (6) and (7)) are not applied at very high altitudes where the Reynolds numbers become small (roughly $Re < 10^4$). At low Reynolds numbers the laminar boundary layer becomes thick, thus greatly increasing skin friction and inducing pressure on the plate (ref. 3). The reduced lift and increased drag (eqs. (2a) and (2b)) combine to substantially decrease the peak lift/drag ratio (refs. 2 and 4). However, if the effects of thick boundary layers are included in the calculation of C_{F_o} and C_{D_o}, equations (3) and (5) should still adequately predict the maximum lift/drag ratio in continuum flow.

[1]The forward part of the underside of the Shuttle has a positive incidence of about 2°, while the aft part is inclined at about -6°.

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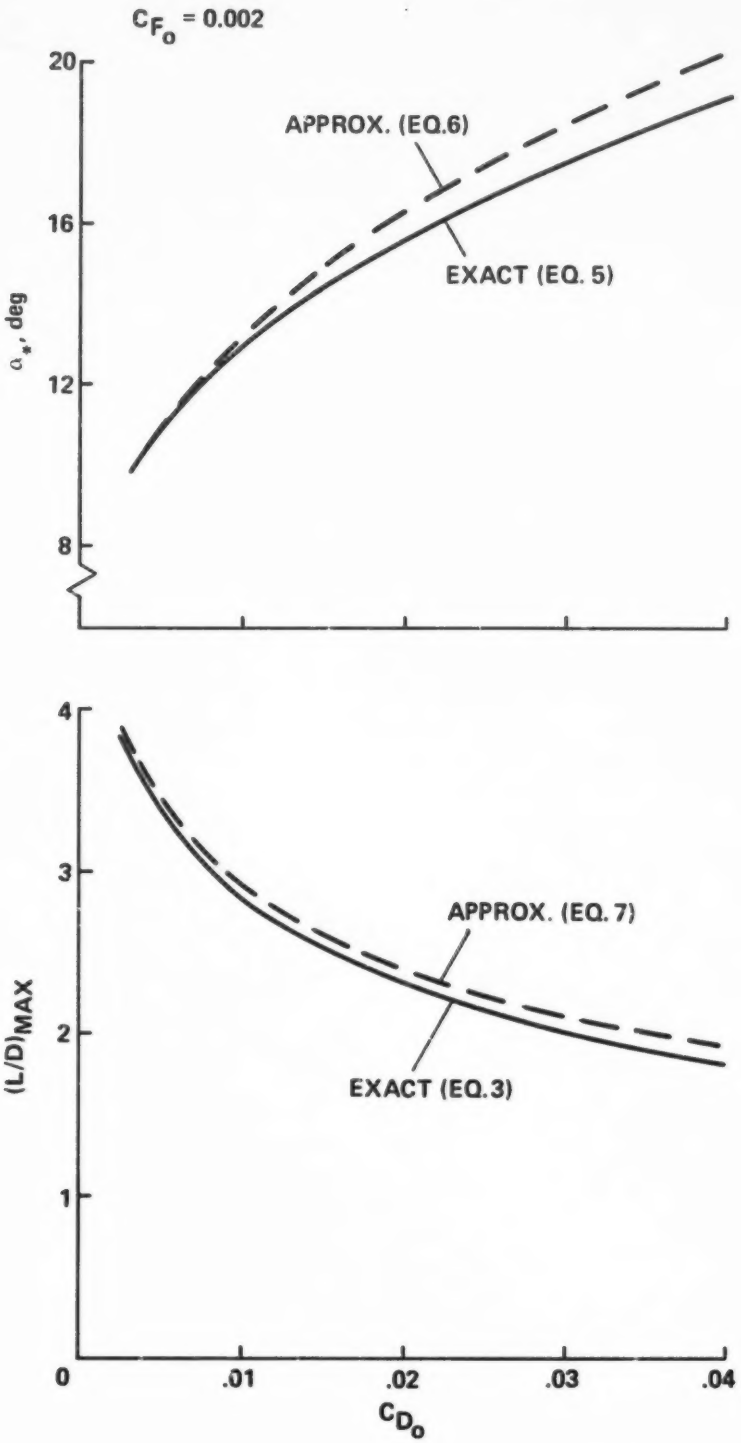

Figure 1.- Optimum angle of attack, α_*, and maximum lift/drag ratio, $(L/D)_{max}$, of a flat plate as a function of bluntness drag coefficient, C_{D_o} (skin friction coefficient = 0.002).

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Point of Contact: Michael E. Tauber, Ames Research Center, MS 230-2, Moffett Field, CA 94035 (415) 694-6086 or FTS 464-6086

16. Abstract

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